TAPER AND FORWARD-FEED IN GaAs MMIC DISTRIBUTED AMPLIFIERS

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ABSTRACT

An improved distributed-amplifier (DA) architecture uses simultaneous inductance tapering and signal forward feeding to obtain additional degrees of freedom for optimization. The approach is illustrated by the design and fabrication of a DA with a predicted gain of 6.9 ± 0.7 dB over a bandwidth of 1-12 GHz.

INTRODUCTION

A distributed amplifier (DA) consists of artificial coupled transmission lines in which the input and output capacitances of active devices (e.g. GaAs MESFETs) become the shunt branches while inductive elements (lumped or distributed) become the series branches. The transconductances of the MESFETs interconnecting the input and output lines provide gain. Absorbtion of MESFET capacitances into the lines yields very broadband operation. Other advantages are (i) that low input and output VSWRs can be maintained over wide bandwidths, so that several DAs can be cascaded without sacrificing gain-flatness, and (ii) that the DA is unconditionally stable if correctly designed.

Contemporary single-chip DAs achieve upper-frequency gains of 10 dB at 18 GHz [1] and 4 dB at 40 GHz [2]; the primary limitations being (i) MESFET channel losses and (ii) skin-effect losses.

The work reported here resulted from the conjecture that the following techniques, used in combination, might yield increased upper-frequency performance within the constraints of a given fabrication process and a given amount of GaAs "real estate":

(a) Varying the line-inductance values to achieve a <u>tapered</u> characteristic impedance.

(b) Inserting inductors in series with each MESFET drain.

(c) In particular, using <u>forward-feed</u> capacitors to compensate for high-frequency gain degradation due to the losses (i) and (ii), above.

Here the effects of these losses on the high-frequency performance of a DA are investigated numerically, using detailed MESFET models. Further simulations show how impedance-tapering, forward-feed capacitors and series-drain inductors can be used together to overcome the high-frequency losses, thereby maximizing the bandwidth.

The approach is illustrated by designing and fabricating a DA with a predicted gain of 6.9 ± 0.7 dB over a bandwidth of 1-12 GHz.

TAPERING

"Tapering" involves progressively increasing the inductor values along the input (gate) line and progressively decreasing the inductor values along the output (drain) line. There are four beneficial effects:

(1) Drain-line tapering maximizes the forward-traveling wave while minimizing the unwanted reverse wave.

(2) Impedance-matching of both gate and drain lines is improved since they now resemble multi-step wideband transformers [3].

(3) The input signals to all MESFETs are equalized, since tapering compensates for line attenuation.

(4) Tailoring group velocities yields enhanced phase concurrency.

FORWARD FEED

"Forward feeding" uses capacitors to route the high-frequency components of each MESFET output signal away from the drain line and toward the gate of the next MESFET. As the frequency increases, signals then tend to propagate through a cascaded rather than a distributed amplifier.

Thus forward feed combines the high-frequency gain characteristics of cascaded amplifiers with the broadband performance and low input/output VSWRs of distributed amplifiers. Although the forward feed principle has been suggested by Ku et al. [4], and [5] reports our preliminary results, this paper presents the first full analytical details.

DESIGN CONSIDERATIONS

The effect of losses on high-frequency gain can be demonstrated using a simplified voltage gain expression [6]. For an unilateral DA in which the drain-line attenuation is equal to the gate-line attenuation:

$$A(\omega)|_{(N_{opt}, W_{opt}, Bias)} = \frac{\omega_T \omega_g}{\omega_{HF}^2} \exp\left[-(\omega/\omega_{HF})^2\right] \quad (1)$$

where

ω = frequency of operation (2)

ω_{HF} = maximum frequency of operation (3)

$\omega_T = g_m/C_{gs}$ (4)

$\omega_g = \frac{1}{R_i C_{gs}}$ (5)

and g_m, C_{gs} and R_i are respectively the transconductance, gate-source capacitance and gate-source resistance of the intrinsic MESFET.

In (1) it is assumed that

(a) both lines have the same characteristic impedance Z_0

(b) the line cutoff frequencies ω_c are both equal to ω_{HF}

(c) the number of MESFET stages has been optimized at $N_{opt} = \omega_g/\omega_{HF}$

(d) the gate width has been optimized at $W_{opt} = \frac{2}{Z_0 k_c \omega_{HF}}$ where k_c is the C_{gs} per unit gate width

(e) the gate periphery has been optimized at $P_{opt} = N_{opt} W_{opt} = \frac{2\omega_g}{Z_0 k_c \omega_{HF}^2}$

(f) the g_m and C_{gs} are proportional to gate width W

(g) the parameters R_i and R_{ds} are proportional to 1/W.

Assumptions (f) and (g) mean that ω_T and ω_g are constants for a particular MESFET process and bias.

From (1) the maximum gain at ω_{HF} is

$$A_{max}(\omega_{HF})|_{(N_{opt}, W_{opt}, Bias)} = \frac{\omega_T \omega_g}{\omega_{HF}^2} e^{-1} \quad (6)$$

i.e., any increase in ω_{HF} is accompanied by a 12 dB/octave gain decrease. **Tapering** and **forward feed** provide ways to overcome this limitation.

RESULTS OF SIMULATIONS

Figure 1 depicts a design incorporating both taper and forward feed. Before investigating its performance we first demonstrate in Fig. 2 the optimized response of some simpler structures:

* Curve 1: an idealized DA with no loss, taper, forward feed, or drain inductors.

* Curve 2: inclusion of lossy MESFETs reduces gain, by as much as 4.5 dB at high frequencies.

* Curve 3: inclusion of both lossy MESFETs and lossy inductors causes a gain reduction of 8 dB at 12 GHz. The response has become unacceptable.

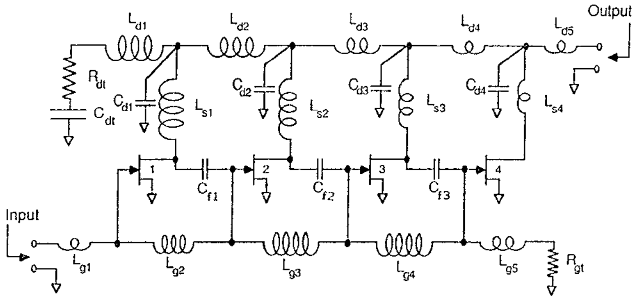

Figure 1. 4-stage distributed amplifier with forward-feed capacitors (C_f) and drain-line shunt capacitors (C_d), as well as tapered gate- and drain-line inductors (L_g, L_d), and series drain inductors (L_s).

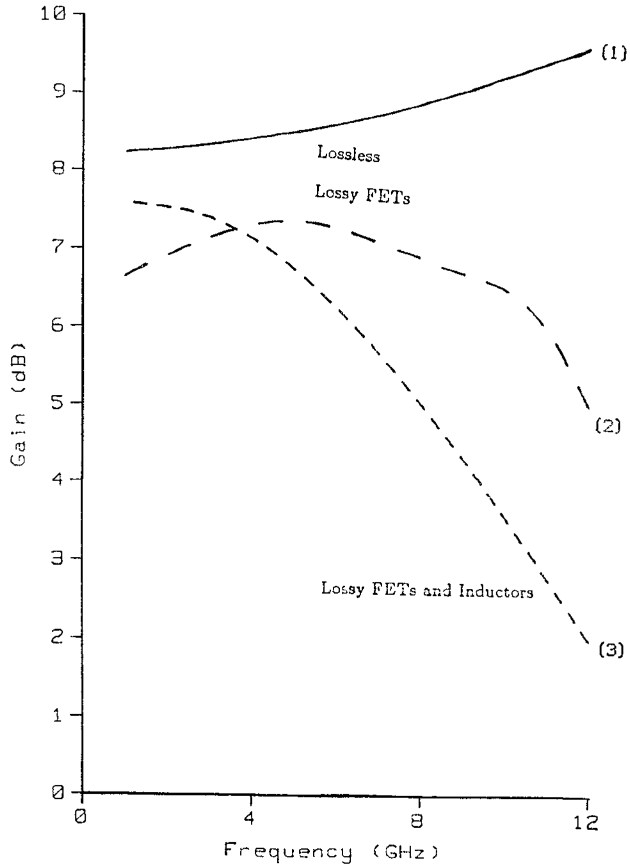

Figure 2. Influence of FET and inductor losses on frequency response of conventional distributed amplifier.

Figure 3 shows the effects of tapering and forward feed. The following computed responses are shown:

* Curve 4: **the gate- and drain-line inductors are tapered**. Above 11 GHz, the gain is improved by 2 dB.

* Curve 5: **tapered series drain inductors are added**. At 8 GHz the gain increases by ~1 dB.

* Curve 6: **addition of forward-feed capacitors** causes a dramatic gain increase.

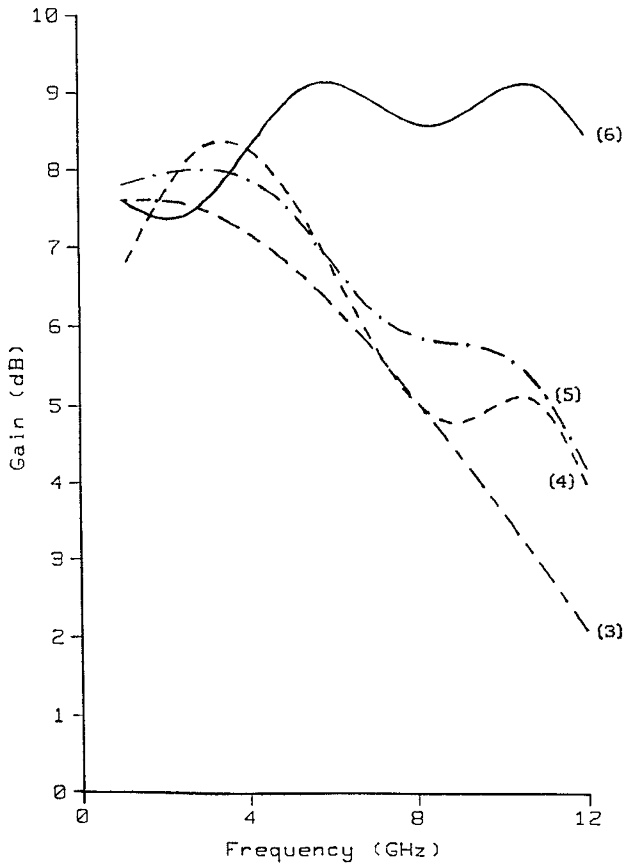

Figure 3. Progressive effects of tapering (4), series drain inductors (5), and forward feed (6) on DA frequency response. Curve (3) is repeated from Fig. 2 for comparison.

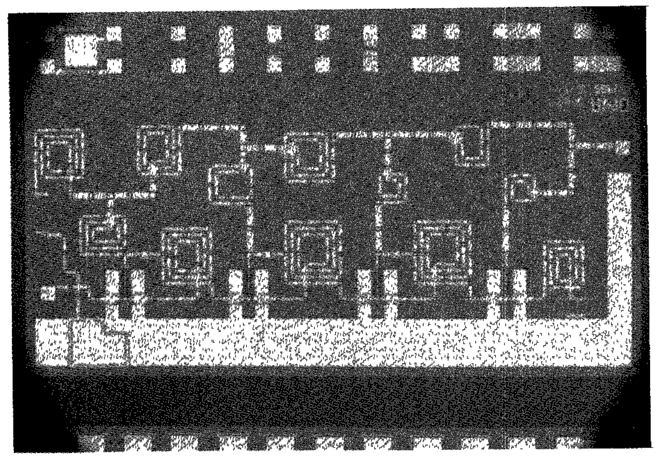

Figure 4. Micrograph of the 4-stage GaAs MMIC DA. The 0.75×1.9 mm chip includes calibration components for coplanar-probe measurements and a wrap-around ground bus. FET dimensions are 1×160 μm.

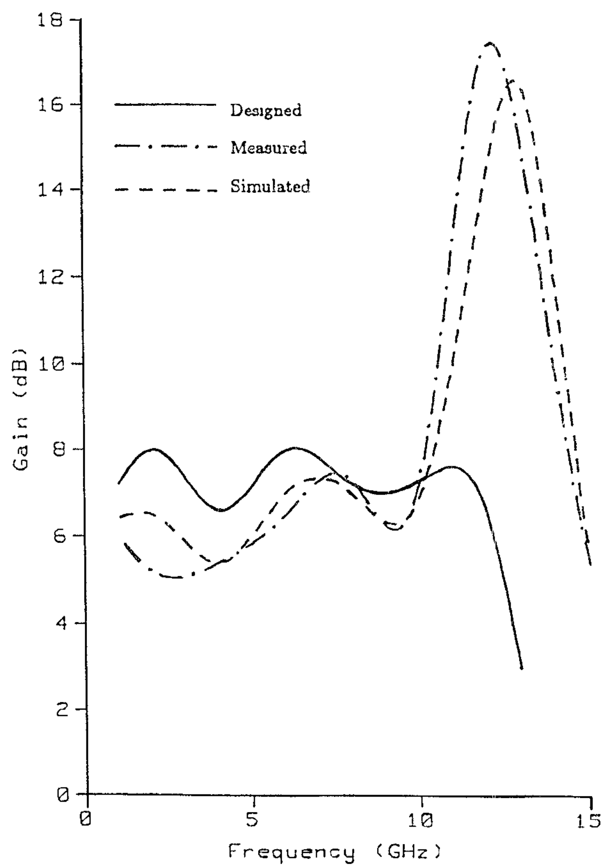

Figure 5. Comparison between designed, measured, and simulated gains of DA.

EXPERIMENTAL RESULTS

A 1-12 GHz tapered DA with the configuration of Fig.1 was designed and fabricated [5]. The chip is shown in Fig.4.

Because the GaAs MMIC fabrication process was altered between the design and fabrication phases, the measured performance differs from predictions. Nonetheless, Fig.5 shows that the designed and measured gains agree within ~1.4 dB up to 10 GHz. The gain peak above 11 GHz is caused by process reductions in R_i, R_{ds} (up to 73%) altering feedback loops such as C_{f1}, L_{g2}; however, the DA remains unconditionally stable. As shown in Figs. 5 to 7, re-calculation of the performance for revised process parameters yields excellent agreement with measurement.

Figures 6 and 7 show that input and output reflection coefficients agree with predictions up to ~ 10 GHz; thereafter process changes again cause disagreement.

This work is believed to be the first reported experimental verification of the simultaneous use of spiral inductors, tapering and forward feed in a GaAs MMIC distributed amplifier.

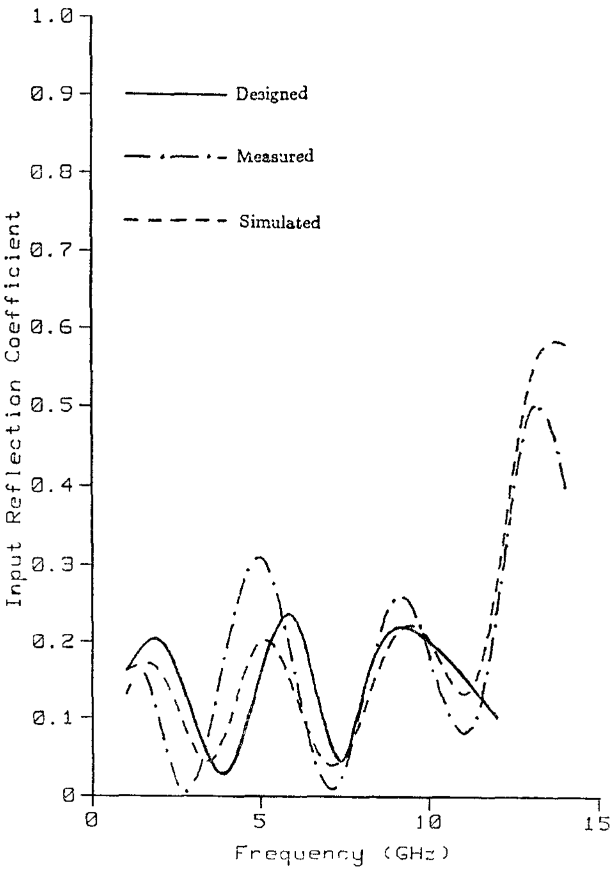

Figure 6. Comparison between designed, measured, and simulated input reflection coefficients of DA.

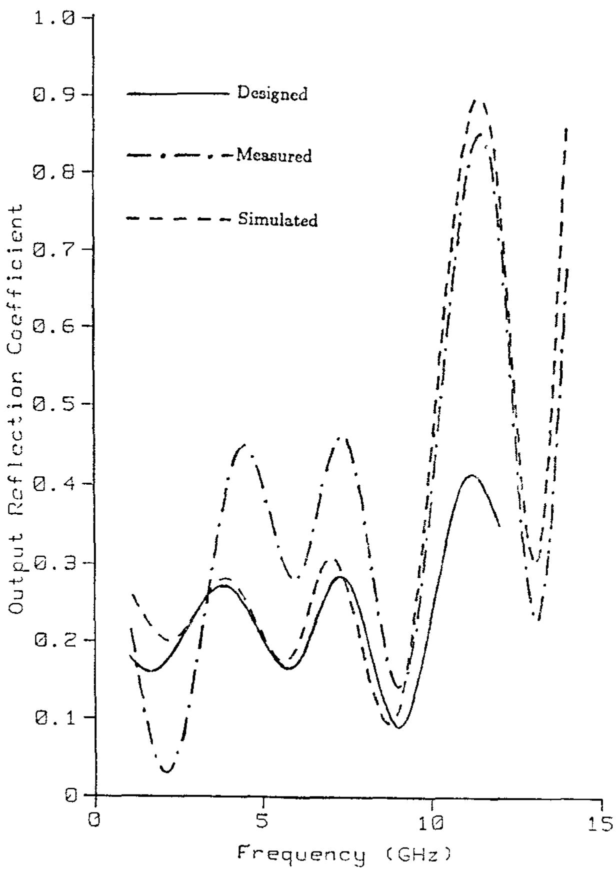

Figure 7. Comparison between designed, measured, and simulated output reflection coefficients of DA.

CONCLUSIONS

We have demonstrated that tapering the values of the gate-line, drain-line and series-drain inductors, together with the use of forward-feed capacitors, are synergic in greatly improving DA gain-bandwidth. The experimental results are the first to support the use of the forward-feed concept. The results also validate the hypothesis that inductor tapering should increase gain and improve the input and output VSWRs.

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